Chapter 4

Microwave Breast Imaging Techniques and Measurement Systems

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Additional information is available at the end of the chapter

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Abstract

Electromagnetic waves at microwave frequencies allow penetration into many optically non-transparent mediums such as biological tissues. Over the past 30 years, researchers have extensively investigated microwave imaging (MI) approaches including imaging algorithms, measurement systems and applications in biomedical fields, such as breast tumor detection, brain stroke detection, heart imaging and bone imaging. Successful clinical trials of MI for breast imaging brought worldwide excitation, and this achievement further confirmed that the MI has potential to become a low-risk and cost-effective alternative to existing medical imaging tools such as X-ray mammography for early breast cancer detection. This chapter offers comprehensive descriptions of the most important MI approaches for early breast cancer detection, including reconstruction procedures and measurement systems as well as apparatus.

Keywords: microwave imaging, breast imaging, breast cancer detection, dielectric properties

1. Introduction

Medical imaging approaches, such as X-ray mammography, ultrasound and magnetic resonance imaging (MRI), play an important role in breast cancer detection [1]. X-ray mammography is the gold-standard method for breast cancer detection, but it has some limitations [2, 3], including harmful radiation, relatively high false-negative rates particularly with patients with dense breast tissue. Ultrasound presents good soft tissue contrast but fails in the presence of bone and air, and the image quality highly depends on operator [4]. MRI allows physicians to evaluate various parts of human body and determine the presence of certain diseases [5], but it is too expensive [6]. Therefore, it is important and necessary to develop a new imaging technique for early breast cancer detection.

In the late 1970s, Larsen et al. obtained the first microwave image of canine kidney [7]. Since then, MI has been intensively studied by many research groups [8–18], and the research objectives have been moved from imaging of organs to application-specific imaging for various tissues such as breast, joint tissues, blood and soft tissues. MI has been recommended as a safe, low-cost and low health risk alternative to existing medical imaging techniques including X-ray mammography and ultrasound. In the past many years, people paid too much attention to the MI algorithms. Several algorithms have been developed and validated numerically and in laboratory environments but they have not extensively validated in clinical environments. Recent clinical trial results demonstrated that more attention should be paid to the hardware implementation system, especially microwave sensors and sensor arrays, in clinical environments rather than laboratory environments.

This chapter presents the basic ideas of MI including currently available breast imaging methods which have been considered as important approaches for early breast cancer detection. The starting point for the development of MI methods is the formulation of the electromagnetic inverse scattering problem. Inverse scattering-based procedures address the data inversion in several different ways, depending on the target itself or on the imaging configuration and operation conditions. In this chapter, electrical properties of biological tissues, MI approaches and biomedical applications and several proof-of-concept apparatuses, including advantages, challenges and possible solutions, as well as future research directions are addressed.

2. Dielectric properties of biological tissues

The dielectric properties (DPs, relative permittivity ε_r and conductivity σ) of malignant tissues at the microwave spectrum change significantly compared to the normal tissue and the dielectric contrast can be detected and imaged by applying MI approaches [19]. The DPs of different types of biological tissues are very different due to water content difference, which are strongly nonlinear functions with frequency [20]. Choosing suitable operating frequencies for the MI system is a critical task, and the attenuation of RF signals increases with frequency due to increase in the conductivity, resulting in a lower penetration depth. Several computer models have been developed to investigate biological tissues. Debye and Cole-Cole models are the most commonly used models. The Debye model simulates the frequency dependence of DPs of tissues sufficiently [21]:

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s + \varepsilon_\infty}{1 + j\omega\tau} - j\frac{\sigma}{\omega\varepsilon_0} \quad (1)$$

where ε_∞ means the permittivity value of the tissue, ε_s is the static permittivity of the tissue, and τ is characteristic relaxation time of the medium.

Cole-Cole model is defined as [22]:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} \quad (2)$$

where ε^* is the complex dielectric constant, ε_s and ε_∞ are static and infinite frequency dielectric constants, ω is the angular frequency and τ is a time constant. The exponent parameter α, which takes a value between 0 and 1, describes different spectral shapes. When $\alpha = 0$, the Cole-Cole model becomes to the Debye model.

Many research groups have investigated DPs of various biological tissues, including breast, heart, skin, liver, bone and lymph nodes [23–31]. Some factors that make effects on DPs of tissues include water content [20], change in the dielectric relaxation time [30], charging of the cell membrane [31], sodium content [31] and necrosis and inflammation causing breakdown of cell membrane [32].

3. Microwave imaging techniques

MI approaches can be classified as passive and active. Passive MI approaches use radiometric to measure temperature differences between normal and malignant tissues and identify the lesions based on the measurement differences. Active MI approaches span the high-MHz to low-GHz regime and appear to offer excellent opportunities to supplement the arsenal of screening tools to the radiologist, despite the fact that MI has yet to reach any demonstrated level of clinical feasibility [33]. This chapter focuses on active MI including tomography and radar-based techniques.

3.1. Microwave tomographic (MWT)

Microwave tomographic (MWT) provides quantitative information of DPs of the imaged object, which makes it possible to identify tissues and materials. One of the major limitations is heavy computation work. Based on the operating frequency of the measurement system, MMT can be grouped as single-frequency and multi-frequency approaches.

Larsen et al. [17] developed the first MWT system to produce a microwave canine kidney image at a frequency of 3.5GHz. The system consisted of one transmitting antenna and one receiving antenna, and antennas and the imaged object were immersed in coupling medium that made of water. During data collection, antennas moved to different positions. Such design was not convenient for practical implantation of MI theory, and long data acquisition time was required. To solve this problem, Hawley et al. [34] developed a new MWT system to measure blood content changes. This system consisted of a circular array of 64 waveguide antennas at an operating frequency of 2.45GHz, each waveguide antenna worked as transmitter and receiver, and mechanical movement was not required in the data collection.

A multi-frequency MWT system for breast cancer detection was developed by Meaney et al. (see **Figure 1**) [35]. The system was made of a cylindrical array of 16 monopole antennas that were placed around a breast phantom. The space between breast phantom and antennas was filled of matching medium that was made from glycerin and water mixture. This system was validated on various numerical breast models and phantoms, and simulation results showed that a small tumor (2 mm in diameter) can be imaged. A good agreement between simulation

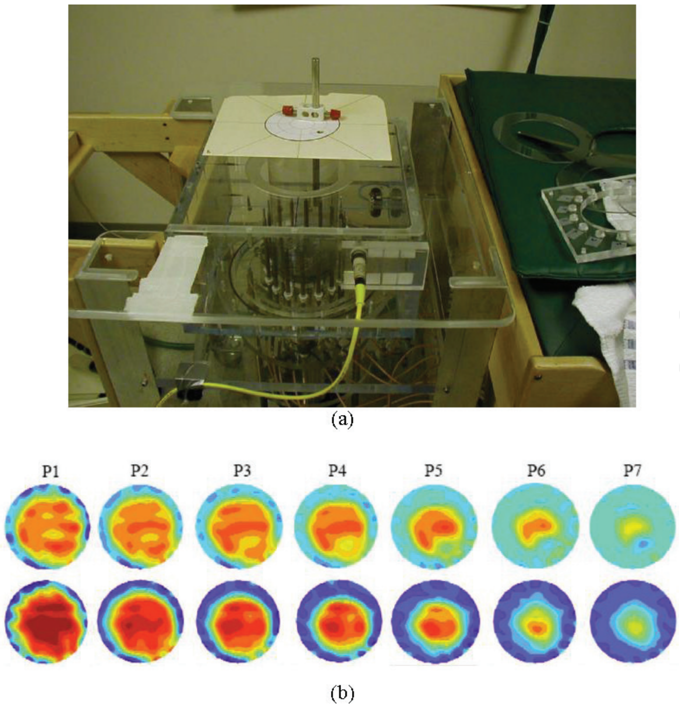


Figure 1. (a) Multi-frequency MWT system for breast cancer detection and (b) microwave (top row, permittivity, and bottom row, conductivity, at 1100 MHz) images in the same anatomically coronal view for the left breast of a woman with fatty to scattered radiographic density. P1–P7 indicates microwave tomograms spaced 1 cm apart beginning near the chest wall.

and experimental results was observed. The same research group also conducted a three-dimensional MWT system for clinical trial, and results showed that breast tumor as small as 1 cm in diameter could be detected [11]. Although clinical results did not achieve a good agreement with experimental results [35], their studies confirmed that it is possible to use MI for breast cancer detection.

3.2. Radar-based microwave imaging

Radar-based MI approaches can be classified into five groups: confocal microwave imaging (CMI), tissue sensing adaptive radar (TSAR), microwave imaging via space time (MIST), multi-static adaptive (MSA) MI, and holographic microwave imaging technique (HMI). This section presents various radar-based MI approaches for breast cancer detection.

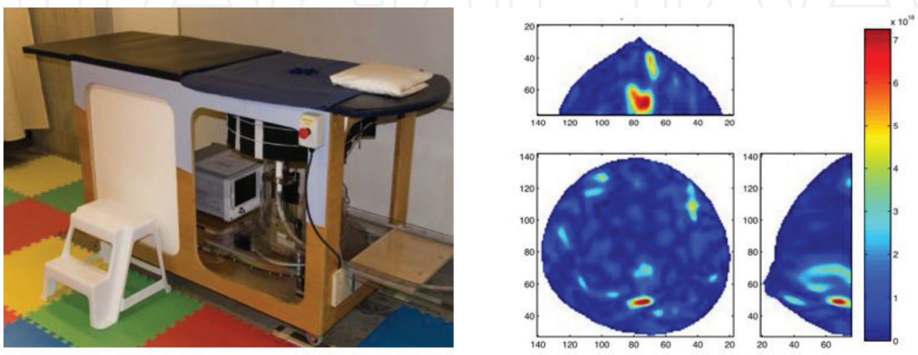
A CMI system was developed by Hagness et al. [13, 14]. In their numerical studies, an array of 17 monopole transceivers was placed along the surface of breast model, and all antennas were equally spaced and spanning 8 cm. Results showed that a small tumor (2 mm in diameter) can be detected by using the 2D system [13], and a tumor with size of 6 mm in diameter can be detected by using the 3D system [14]. The CMI provides necessary imaging resolution and adequate penetration depth in the breast. It does not compensate for frequency-dependent propagation effects but has limited ability to discriminate against artefacts and noise. To overcome these challenges, they applied delay multiply-and-sum signal processing with CMI, where the scattered signals were time-shifted, multiplied in pair and the products were summed to form a synthetic focal point [15]. This method has an ability to produce higher resolution image and high interference rejection capability [16].

A TSAR prototype system as shown in **Figure 2(a)** was developed by Fear et al. [18]. During data acquisition, a patient was lying in prone position on the examination table with her breast extending through the breast hole and the antennas was scanned around the breast. In order to reduce the noise, the breast image was formed from the reflection signals without skin reflections. Clinical results (see **Figure 2(b)**) showed that the TSAR has an ability to detect and localize lesions with size greater than 4 mm in diameter. The major limitations of TSAR include the large reflections caused from the skin and expensive electronics for real-time imaging. To solve these problems, a Bayesian estimator was applied to enhance the reconstructed image [36].

A MIST beam-forming was developed by Bond et al. [16, 37–38]. A planar array of 16 horn antennas was placed close to the surface of the breast model, and a UWB signal was transmitted sequentially from each antenna. Numerical results demonstrated that a small tumor (2 mm in diameter) embedded in the heterogeneous breast tissue were successfully detected even with denser breast tissue. MIST offers significant improvement in performance over UWB MI approaches based on simpler focusing schemes. However, the system caused skin-breast artefacts in the image prior. The research team upgraded the imaging system (see **Figure 3(a)**) to overcome the challenges of detecting, localizing and resolving multiple or multifocal lesions [39]. The experimental results demonstrated that tumors with size of 4 mm in diameter could be imaged (see **Figure 3(b)**).

Recently, Smith et al. [40–43] proposed a near-field indirect HMI method, which involves recording the holographic intensity pattern and reconstructing the image by using Fourier transformation from the recorded intensity pattern. Compared to TSAR, indirect HMI has the ability to produce real-time image at a significantly low cost. However, more validation works are required on the theory and proof-of-concept for medical applications.

More recently, the authors proposed a far-field HMI method for imaging of biological objects [44–46]. Different from IHM, the 3D HMI uses physical displacement (scan of the distance)



(a) (b)

Figure 2. (a) TSAR prototype system and (b) TSAR images for patient.

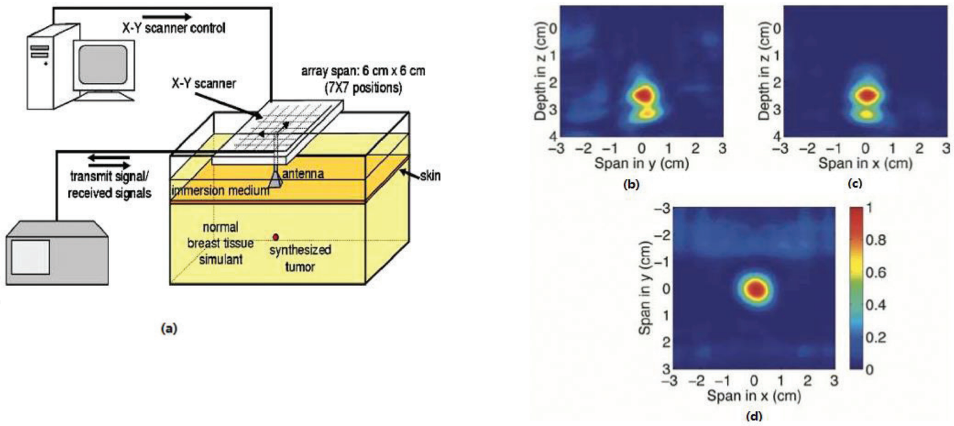


Figure 3. (a) MIST experimental system setup; reconstructed images with a 4-mm-diameter tumor; (b) yz-plane at x = 0.1 cm; (c) xz-plane at y = 0.1 cm and (d) xy-plane at z = 2.3 cm [39].

between the sensor array plane and the imaged object over a specified range (vertical) to obtain the depth information from sequenced 2D images. Both simulation and experimental results demonstrated that the HMI has several advantages in data collection, including that no matching medium was required and that the complex permittivity of the object was not required to calculate to generate an image that reduced the imaging reconstruction time.

3.3. Imaging systems

Most of existing active MI measurement systems involve hardware and software parts. The hardware system generally includes a microwave source generator, transmitting antenna(s) to send microwave signals toward the target object, receiving antennas(s) to measure the scattered electric field from the target object, a signal measurement controller to control antennas and antenna array plane, and a host computer that contains a matched software system to analyze the measured data using image processing algorithm to display the reconstructed image on a screen displaying unit. The transmitter and receiver can use the same sensor. The requirements for the hardware systems and the computational power are different due to the image algorithm differences. **Table 1** presents various developed MI systems.

3.3.1. Microwave sensor

To design an efficient and robust MI system, it is necessary to develop a sensor to match specific requirements including operating frequency, bandwidth, directivity, sensitivity, accuracy of the detection and many other factors such as compact size and low cost. Sensors should be designed specifically for lower frequencies to enhance electric field intensities inside biological tissues, due to more penetration inside the tissue when the frequency is relatively low; thus, more useful information of the object can be obtained. Various sensors have been developed for imaging of breast, including open-ended coaxial probe [47–57], tapered slot antenna (TSA) [59–63], bow-tie antenna [64–70], monopole antenna [71–78], dipole antenna [79, 80], waveguide antenna [81–84], patch antenna and Vivaldi antenna.

	Dartmouth College (USA)	Keele University (UK)	University of Bristol (UK)	University of Manitoba (Canada)	Auckland University of Technology (NZ)
Antenna	Circular array of 16 monopoles	Circular array of 24 ceramic-filled open-ended waveguides	Two spherical arrays consist of 31 and 60 ultra-wideband antennas	Circular array of doubled layers Vivaldi antennas	Spiral array of 16 open-ended waveguide antennas
Frequency	0.5–3 GHz	1.0–2.3 GHz	4–8 GHz	3–6 GHz	12 GHz
Test phantom	Real patients	Soft animal tissues	Real breasts	Various dielectric objects	Various dielectric objects
Immersion medium	0.9% saline (ε_r = 76.6, Σ = 2.48 S/m)	Metallic bath with coupling liquid	Matching ceramic	No matching medium, air only	No matching medium, air
Image	2D and 3D	2D	3D	2D	2D and 3D
Clinical trial	Yes	No	Yes	No	No

Table 1. Various MI measurement systems.

Open-ended coaxial probes were employed in MI systems to measure dielectric properties of biological tissues [47–56]. Advantages of using probes include that tissue manipulation or preparation is not required, dielectric-properties measurements can be integrated in a straightforward manner with surgical and pathology protocols, they are easy to use, they can respond at broadband frequencies and there is a capacity for noninvasive measurements. However, accuracy and reliability of the measurements depend on the aperture of probe as it is the only part of the system in direct contact with the imaged object.

A compact tapered slot antenna (TSA) was applied in an UWB MI system by Bialkowski et al. [58], and the benefits include high directivity, wide bandwidth, simple feed structure and relatively low in cost, which makes TSA become a popular choice for implementation of MI systems [59–63].

UWB bow-tie sensors were used by John et al. [70]. The system is made of an imaging cavity formed from 12 panels soldered together, and each panel is made of three UWB bow-tie sensors as shown in **Figure 4**. The coupling medium was filled in the cavity, and an image of a spherical object was reconstructed by using inverse scattering algorithm. Advantages of using bow-tie sensor include compact, wideband and easy-to-manufacture.

Researchers at Dartmouth College developed an MWT system that is made of a cylindrical array of 16 monopole antennas (see **Figure 1**), one antenna acting as transmitter and others acting as receivers, and sensors were placed in a coupling medium that is made of material close to fatty tissues. The system was validated on breast phantoms and real human subjects [35]. Advantages of using monopole antennas include easy to model, compact, can be placed at different geometries and can be impedance-matched across a wide bandwidth when immersed in a lossy medium.

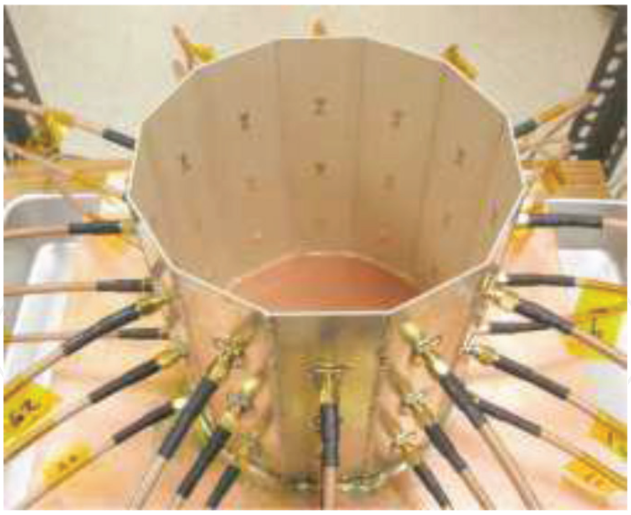


Figure 4. Imaging cavity demonstrated in John's publication [82].

Open-ended waveguide antennas were applied in the HMI system by the authors [46]. The HMI system was made of an array of 16 open-ended waveguide antennas, one acting as transmitter and other being receivers. During data collection, the transmitter continuously generated RF signals to the breast phantom and the scattered electric fields were measured by receivers. No matching medium was required in this measurement system.

3.3.2. Microwave sensor array

Investigators also studied the performance of producing high-resolution images at lower costs, including image algorithms, sensor design and sensor array geometry. People paid much attention to image algorithm and sensor design, but very little attentions have been paid to sensor arrays and their applications in the biomedical field. Most of the existing MI systems use circular- [18], planar- [38] and spherical [85]-shaped sensor array. The circular sensor array is more suitable for clinical settings. To generate a high-resolution image, a large number of sensors (from several to several hundreds) are required for the existing MI system. The image is improved with increasing the total number of sensors used in the system. However, limitations of increasing sensor numbers include the increased cost, size and complexity.

Recently, Klemm et al. [85] proposed a spherical array of 16 patch antennas for the clinical applicable CMI system. During data collection, the patient was lying in a prone position, which was felt to offer the best chance of the breast forming a gentle and uniformly curved shape. Experimental results showed that the image quality can be improved by improving the bandwidth of the array element.

More recently, the authors [46] proposed a spiral and random sensor array that contains 16 waveguide antennas for HMI system as shown in **Figure 5**. The experimental results showed that the breast phantom image can be improved by using spiral and random sensor arrays compared to the regular spaced sensor array. Color bar plots signal intensity on a linear scale.

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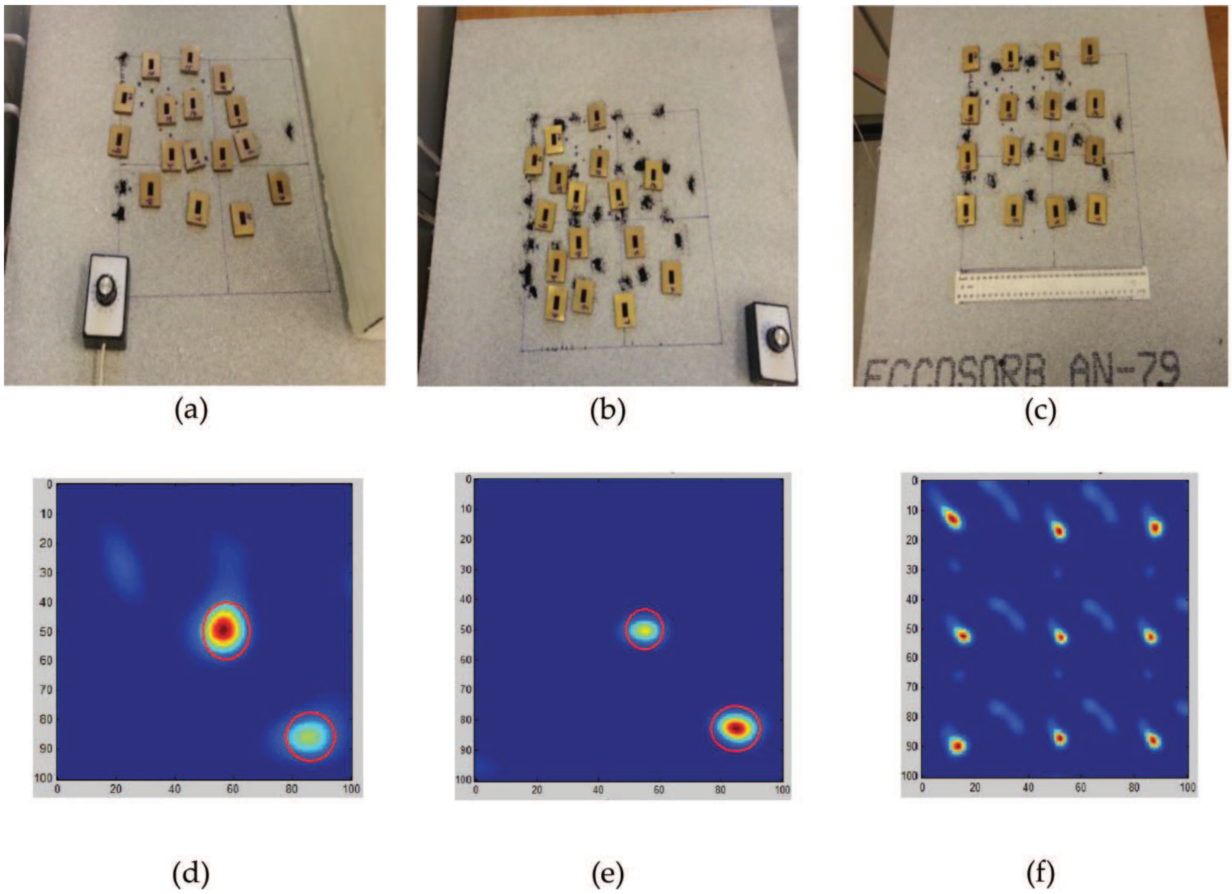

Figure 5. (a) Spiral array; (b) random array; (c) regularly spaced; reconstructed images of two inclusions using (d) spiral array; (e) random array and (f) regularly spaced array.

4. Challenges and future work

There are several major limitations for practical implementations of MI approaches. First, breast phantoms were made of simple materials, which cannot represent real human tissues accurately. Second, the electrical properties contrasts between the normal and the malignant tissues are much smaller than people thought, which caused more difficultly in imaging the structures. Choosing a suitable operating frequency range is also a challenging task. These challenges can be solved by developing a high dynamic system to capture the small difference in the scattered field or by developing a contrast agent to enhance the electrical properties of the malignant tissues. The spatial resolution is another major challenge. To enhance spatial resolution of an MI system, many researchers increased the number of microwave sensors for the implementation system. For example, the sensor number has been increased from 16 to 256 to increase the image quality [86]. However, the detection accuracy may be reduced due to the mutual coupling signals produced between sensors. Moreover, the system became very complex and the implementation costs increased significantly.

To address these problems, one single scanning antenna may be used instead of several antennas. Investigation of sensor arrays such as unequally spaced sensor arrays and applying compressive sensing approach [87, 88] may be another solution. Some recently proposed techniques such as multiple-input-multiple-output technique [89] may be able to reduce the complexity of the system. Finally, most of the existing experimental systems require the coupling medium between sensors and the imaged object, which increased the system cost significantly.

Many promising indicators suggested that MI systems in the future will be a successful clinical complement to conventional mammography. Investigations may improve the imaging algorithms and hardware implementation systems with particular focus on highly sensitive, compact and low-cost microwave sensors and sensor arrays to achieve high-quality images at relatively low cost. Significant contributions from existing MI commercial companies may be greatly helpful in developing the well-established MI modalities to clinical trials.

5. Conclusion

In conclusion, this chapter presented an exhaustive summary of MI approaches with particular focus on implementations of microwave breast imaging theory, including image algorithms, experimental setups, microwave sensors and sensor arrays. Several MI implementation apparatuses were reviewed in detail. MI systems have direct impacts on spatial resolution, operating frequencies, detection accuracy and quality of imaging. Several advantages of existing MI approaches, open challenges, possible solutions and future research directions were also discussed. Successful clinical trials of MI for breast imaging made the worldwide excitation, and this achievement confirmed that MI has potential to become a low-risk alternative to existing medical imaging tools such as X-ray mammography for breast cancer detection. However, MI-based techniques are still far from maturity due to the fact that many challenges have to be addressed before MI can be implemented in clinical environments.

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